HYBRID FUZZY- PROPORTIONL INTEGRAL DERIVATIVE CONTROLLER (F-PID-C) FOR CONTROL OF SPEED BRUSHLESS DIRECT CURREN MOTOR (BLDCM)

FARAG A. M. ELKARGHALI

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Electrical Engineering

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

December 2017

Dedicated with gratitude to my country Libya for the huge support and giving me this opportunity to study overseas.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ACKNOWLEDGEMENT

First and foremost, my praise to Almighty Allah for giving me the power and persistence to complete this study and peace be upon his final Prophet and Messenger Mohammed, SAW.

I would like to express my sincere appreciation to my supervisor, Dr. Asmarashid Ponniran for the guidance and constant given support throughout the duration for this research.

I have to thank my dearly loved parents for their love and support throughout my life. Thank you both for giving me strength to reach for the stars and chase my dreams. My mother and brother deserve my wholehearted thanks as well.

To my treasured wife, a very special thank you for your emotional support and unending love. I could not do it without you.

Last but not least, my great thankful to all my friends who stood beside me and pushed me forward to complete my studies.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRACT

Hybrid Fuzzy proportional-integral-derivative (PID) controllers (F-PID-C) is designed and analyzed for controlling speed of brushless DC (BLDC) motor. A simulation investigation of the controller for controlling the speed of BLDC motors is performed to beat the presence of nonlinearities and uncertainties in the system. The fuzzy logic controller (FLC) is designed according to fuzzy rules so that the systems are fundamentally robust. There are 49 fuzzy rules for each parameter of FUZZY-PID controller. Fuzzy Logic is used to tune each parameter of the proportional, integral and derivative (k_p, k_i, k_d) gains, respectively of the PID controller. The FLC has two inputs i.e., i) the motor speed error between the reference and actual speed and ii) the change in speed of error (rate of change error). The three outputs of the FLC are the proportional gain, k_p, integral gain k_i and derivative gain k_d, gains to be used as the parameters of PID controller in order to control the speed of the BLDC motor. Various types of membership functions have been used in this project i.e., gaussian, trapezoidal and triangular are assessed in the fuzzy control and these membership functions are used in FUZZY PID for comparative analysis. The membership functions and the rules have been defined using fuzzy system editor given in MATLAB. Two distinct situations are simulated, which are start response, step response with load and without load. The FUZZY-PID controller has been tuned by trial and error and performance parameters are rise time, settling time and overshoot. The findings show that the trapezoidal membership function give good results of short rise time, fast settling time and minimum overshoot compared to others for speed control of the BLDC motor.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRAK

Pengawal (F-PID-C) Hibrid Kabur berkadaran-kamiran-terbitan (PID) direka dan dianalisis bagi mengawal kelajuan motor DC (BLDC) tanpa berus. Suatu penyiasatan simulasi bagi pengawal yang mengawal kelajuan motor BLDC dijalankan untuk menghalang kewujudan ketidaklinearan dan ketidakpastian di dalam sistem. Pengawal logik kabur (FLC) direka berdasarkan peraturan kabur supaya sistem-sistem teguh pada dasarnya. Terdapat 49 peraturan kabur bagi setiap parameter pengawal FUZZY-PID. Logik kabur digunakan untuk menala setiap parameter bagi gandaan-gandaan berkadaran, kamiran dan terbitan (k_p, k_i, k_d), masing-masing bagi pengawal PID. FLC mempunyai dua input iaitu, i) ralat kelajuan motor antara rujukan dan kelajuan sebenar, dan ii) perubahan dalam kelajuan daripada ralat (kadar bagi ralat perubahan). Tiga output daripada FLC iaitu gandaan berkadaran; k_p, gandaan kamiran; k_i dan gandaan terbitan; k_d, gandaan-gandaan akan digunakan sebagai parameter bagi pengawal PID dalam mengawal kelajuan motor BLDC. Pelbagai jenis fungsi keahlian telah digunakan dalam projek ini seperti Gaussan, trapezoid dan bersegi tiga dinilai dengan kawalan kabur dan fungsi keahlian ini digunakan dalam FUZZY PID bagi analisis perbandingan. Fungsi-fungsi keahlian dan peraturan-peraturan telah ditakrifkan menggunakan editor sistem kabur yang diberi dalam MATLAB. Dua situasi yang berbeza telah disimulasikan, iaitu sambutan mula, sambutan langkah dengan beban dan tanpa beban. Pengawal FUZZY-PID telah ditala dengan kaedah cuba-cuba dan prestasi parameter, iaitu masa naik, masa pengenapan dan lajakan. Dapatan menunjukkan fungsi keahlian trapezoid memberikan keputusan baik bagi masa naik yang pendek, masa pengenapan yang pantas dan lajakan minimum dibandingkan dengan yang lain-lain bagi kawalan kelajuan motor BLDC.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CONTENTS

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

BLDCM	- Brushless Direct Current Motor
FLC	- Fuzzy Logic Controller
PID	- Proportional Integral and Derivative
F-PID-C	- Fuzzy- Proportional Integral and Derivative- Controller
EMF	- Electromotive Force
PSO	- Particle swarm optimization
MF	- Membership Functions
DC	- Direct Current
AC	- Alternative Current
PMSM	- Permanent Magnet Synchronous Motor
PWM	- Pulse Width Modulation Techniques
T_P	- Peak Torque
T_R	- Rated Torque
SISO	- Single-Input-Single-Output
MIMO	- Multi-Input-Multi-Output
C_1	- Controller
C_2	- Plant
Z	- Sensor
$C_1(s)$,	- Transfer Function Elements
$C_2(s)$,	- Transfer Function Elements
$Z(s)$	- Transfer Function Elements
$y(t)$	- The Measured Output)
$r(t)$	- The Desired Output
$e(t)$	- Tracking Error
k_p	- Proportional Gain
k_i	- Integral Gain
k_d	- Derivative Gain

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

$C(s)$	- Correcting Terms
$MV(t)$	- Manipulated Variable
P_{out}	- Output Proportional Term
I_{out}	- Output Integral Term
D_{out}	- Output Derivative Term
τ	- A dummy Integration Variable
t	- Time or Instantaneous Time
V_{al3} V_{al1}	- Membership Boundaries of Triangular
V_{al2}	- Membership Boundaries of Triangular
V_{al1}, V_{al3}	- Membership Boundaries of Trapezoidal
V_{al2}, V_{al4}	- Membership Boundaries of Trapezoidal
X_p	- The Midpoint
w	- The Width of Bell Function
$\mu(u_i)$	- Bell Membership Function
P_B	- Positive Big
N_B	- Negative Big
N_S	- Negative Small
Z	- Zero
N_M	- Negative Medium
P_S	- Positive Small
P_M	- Positive Medium
MAX	- Max Criterion Method)
COA	- Centroid Method or Center of Area Method
U_o	- Final Output
v_{bs},v_{cs},	- Phase Voltages
R_a, R_b, R_c	- Stator Resistance Per Phase
$i_a,\ i_b\ \ i_c$	- Stator Phase Currents
$e_a\ , e_b\ \ e_c$	- The Phase Back Electromotive Forces
L_{ab}, L_{bc}	- Mutual Inductances Between Phases a, b and c
D	- Differential Operator
T_e	- Electromagnetic Torque (N ·m)
ω	- Motor's Mechanical Angular Velocity (rad/s)
n_p	- Rotor Pole Pairs.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

T_l	-	Load Toque
J	-	Rotor Moment of Inertia
R_N	-	Number of Rules =, and =
M	-	Number of Membership Functions
N	-	Number of Inputs
Ce	-	Change of Error
e	-	Error
t_s	-	Settling Time
m_p	-	Rise Time
t_r	-	Overshot

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDICES

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 1

INTRODUCTION

1.1 Background

Motor drives with high performance efficiency are vital in several industries and have found application in many areas such as electric automotive, robotics, rolling mills, aviation, electric trains, and robotics [1]. Electric motors in different forms have been suggested for use in applications [2], among which the DC motors stands out. Contrarily, there are several disadvantages of the conventional DC motor, including the need for a routine maintenance of the commutators, high initial cost, and frequent changing of the brushes [3].

The conventional DC motors are not ideal in explosive or clean environments. An alternative to the DC motor is the Squirrel cage induction motor which more robust and commands an initial low cost. Meanwhile, a low power factor and starting torque are the major problems of the Squirrel cage induction motor [4]. Additionally, both the induction and conventional DC motors are not suitable for high-speed use. Another alternative to the DC and induction motors for high speed application is the brushless DC motors. The brushless DC motor is notorious for high speed usage [4]. There are several advantages of the BLDC motors over brushed DC motor; these include having longer life, immunity to noise, higher efficiency, relatively small, requiring less maintenance since there are no brushes, and

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

commutator arrangement. The BLDC, as the name suggests, uses electronic commutation for commutation instead of brushes, which makes it a virtually [5]. There are other advantages of the BLDC motor over the induction motor, including having a better speed - torque characteristics, longer operating life, high dynamic response, and operating noiselessly, which made it a dominant electric motor [6].

1.2 Problem statement

BLDC motors require suitable speed controllers to accomplish desired level of performances. Normally, proportional integral and derivative (PID) controller is used for the control of the speed. Though the conventional PID controllers are mostly used industrially owing to the simple structure of their operation and ease of implementation, they pose problems in the presence of control technique like sudden change in setpoint and, parameter variation (k_p,k_i,k_d) not produce automatically and these parameters need to tune, it makes the PID control gives poor response, and nonlinearity, the non-linearity arises due to armature current limitation and change in loads. Furthermore, the PID controller is difficult to tune the parameters and get satisfied control characteristics [7].

Being that BLDC motors have nonlinear model, the PID controllers are not ideal to be used. In addition, traditional PID controller cannot be used in systems with unstable parameters because the PID constant will be required to be changed often [4]; also, the BLDC motor may cause serious overshoots because it has high start torque which are not desired in most conventional controllers like PID. In this way, the BLDC motor drives system need appropriate controllers like the fuzzy PID controllers (F-PID-C) to govern the startup response, decrease overshoot and steady-state error to meet the system demands [8].

The F-PID-C is an extension of the conventional technique because of its maintenance of the linear structure of PID controllers. The F-PID-C was designed based on the basic F-PID-C principle to achieve a good controller with analytical formulas like the other smart controllers. The F-PID-C has variable control gains within their linearity structure which are nonlinearity functions of the error and the rate of changes in the error signals. They can improve the overall performance of the

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

BLDC motor owing to their characteristic features such as the self-tuned mechanisms which can adjust to error variations and rate of error changes caused by time delay, nonlinearity and process uncertainties [9].

In this research, three types of membership functions (MF) of F-PID-C model for the control of BLDC motor will be designed and compared between each other to achieve the best model.

1.3 Research Objectives

The study objectives are:

i. To analyze the transient characteristics of BLDC motor, i.e., by overshot amplitude, steady-state error and rise time using Fuzzy-PID controller based on three types of membership functions, i.e., Gaussian, Trapezoidal and Triangular.
ii. To compare between three different types of MF by Fuzzy PID control on the BLDC motor.
iii. To compare between two controller Fuzzy-PID controller and Fuzzy-PI controller

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

1.4 Scope of Project

i. Using Simulink in MATLAB to implement fuzzy PID controller to control the speed of the BLDC motor.
ii. Design three type of Membership functions and rules using Fuzzy Toolbox in MATLAB.
iii. Simulation of the BLDC motor model on a MATLAB Simulink platform and developed FLC system.

CHAPTER 2

FUZZY-PID CONTROLLER CONCEPT AND BLDC MOTOR ASPECTS REVIEW

2.1 Introduction

This chapter describes the literature review of BLDC motor, PID controller and Fuzzy logic control system. In this chapter, also will discuss some researches that are relevant to this project to demonstrate continuity from the previous researches.

2.2 Previous case study

The speed and current controllers of BLDC motor with non-sinusoidal (trapezoidal) back-electromotive force have been investigated previously [10]. Faster drives with reduced ripples in current and torque and smoother speed response are often desired. In many applications, BLDC motors are controlled using back EMF. This work implements a simple control scheme which have no need any complicated calculation, or knowing the back EMF and shape functions. To address the issues of the conventional PID speed controllers, the Fuzzy logic speed controller is being set forth for the reduction of the starting current, elimination of torque overshoot, and

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

achieving a fast speed response. The design is simple and does not require any complex computation. Simulation studies were conducted to validate the effectiveness of the proposed system in controlling the performance of BLDCM. A robust control was achieved with the proposed algorithm via MATLAB simulation.

An adaptive F-PID-C for controlling the speed of DC brushless motor has a wide industrial application, such as in the servo motor drives, automobile, medical, and aerospace has been studied [11]. There are many advantages of the electronically commutated BLDC motors over the brushed DC motor, such as having longer life, lower volume, increased efficiency, and higher torque. This study employed Simulink model to analyze the performance of F-PID-C and adaptive F-PID-C. The tuning and computation of parameters using the normal PID controllers is difficult and when compared to the adaptive fuzzy PID controllers, does not produce satisfactory control features. The simulation studies verified a better performance of the adaptive F-PID-C compared to the F-PID-C. The BLDC motor was modelled and controlled using the SIMULINK software package.

A new P-fuzzy self-adaptive PID intelligent method based on the BLDC motor mathematical model has been proposed [12] for the control of the speed of a servo system. In the BLDC motor control system, current hysteresis is applied in the current loop, while the P and fuzzy self-adaptive PID hybrid control scheme is applied in the speed loop. To organically combined the blocks, a double close loops timing system with current hysteresis and fuzzy speed control was tested and the simulation results showed that the system has an improved accuracy, reduced response time, controlled overshoot, achieved fine robustness, was self-adapting, and obviously performed better compared to the ordinary proportional-integral, differential (PID) control. The model was validated and verified, and thus, a novel approach was provided for further motor studies.

An optimized fuzzy logic controller based on the particle swarm optimization (PSO) for the control of DC motor speed has been proposed [13]. The simulation of the controller model was carried using MATLAB software and tested on a laboratory DC motor experimentally. The performance of several controllers such as fuzzy logic controllers, PID controllers, and optimized fuzzy logic controllers was compared as well. Simulation and experimental results showed that the suggested fuzzy logic control (FLC) and PSO speed controllers had better dynamic performance compared to the normal FLC and PID controllers. Furthermore, it had a better performance on

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

the DC motor with a perfect speed tracking devoid of overshoots. With heuristically defined MF, the optimized membership functions (MF) offered a better performance and higher robustness compared to the regular fuzzy model. Furthermore, the ability of proposed FLC under sudden load torque changes which can result in speed variances was experimentally verified.

2.3 Brushless direct current motors (BLDC)

Several applications demand electric motors with a range of speed and torque control and the DC machine met these criteria though it needs a periodic maintenance. Like the induction and brushless permanent magnet motors, the AC machines have no brushes and are designed with robust rotors due to the absence of a commutator and/or rings, meaning a very low maintenance is required. The efficiency and power-to-weight ratio are also enhanced by this arrangement. Flux control that offers a high dynamic performance has been designed for induction motors in some applications, such as in electric traction. However, this is still a sophisticated and complex control system [14].

The hardware of most application controls has been simplified through the development of the machines with brushless permanent magnets. There are currently two types of machines with brushless permanent magnet, of which the most popular is the permanent magnet synchronous motor (PMSM), which is supplied with sinusoidal currents. The second type is the brushless DC (BLDC) motor which is supplied with quasi- square-wave currents. In these two designs, the rotor copper losses are eliminated, giving a high peak efficiency when compared to the conventional induction motor [15].

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

2.3.1 The development and operation strategy of the BLDC motor

The BLDC motor is a form of motor in which the magnetic field from the stator and the rotor twirls are equal in frequency (synchronous motor). The “slip” that is common with the induction motors is not experienced in the BLDC motors. The magnet rotor and wire -wound stator poles are permanently built in the BLDC motor [16].

2.3.1.1 Stator

The BLDC motor stator has a stacked steel laminations with windings which are maintained in the axially cut slots along the inner surface Figure 2.1. There are 3 stator windings in most BLDC motors which are interlinked in a star fashion and these windings are generated from various coils that are linked to derive a winding. Windings are formed from one or more interconnected coils and maintained in the slots; each winding is distributed over the stator periphery to form an even number of poles [16].

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

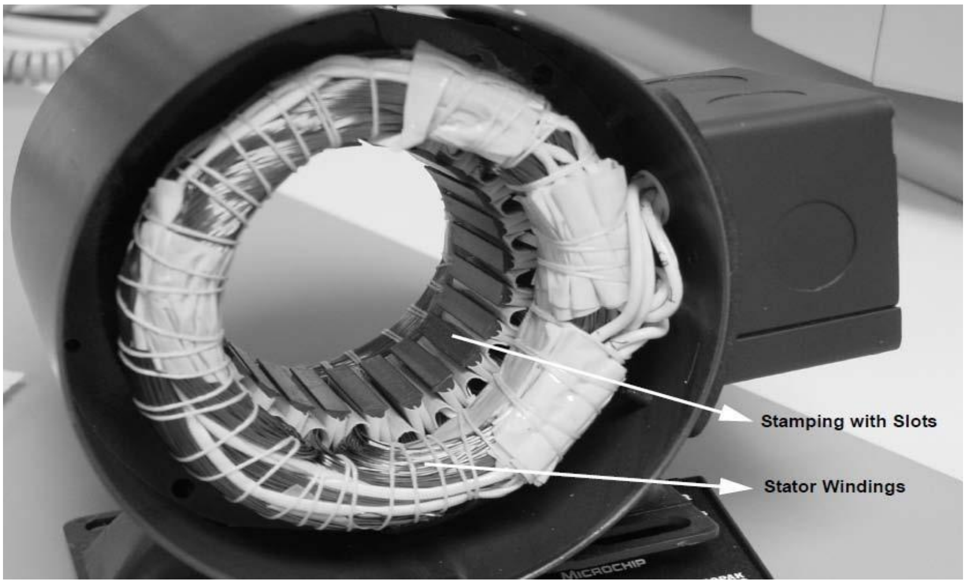

Figure 2.1: The stator of BLDC motor [16]

2.3.1.2 Rotor

Figure 2.2 shows rotor magnetic of a BLDC motor. Permanent magnets form the rotor of the BLDC and can be alternated between 2 and 8 pole pairs with alternate N and S poles. The field density of the rotor in a motor determines the suitable magnetic materials to be selected; the permanent magnets are made with ferrite magnets, but these days, rare earth alloy magnets are attracting attention [17].

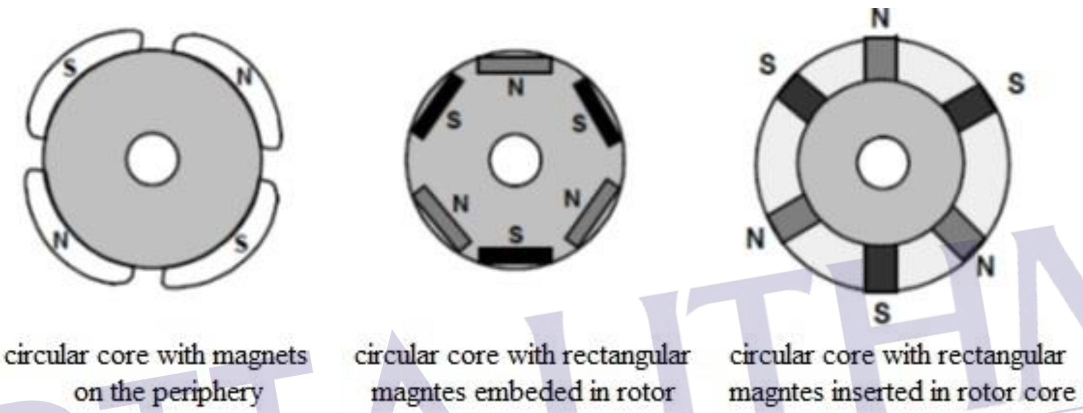

Figure 2.2: Rotor magnet cross section [17]

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

2.3.1.3 Hall sensors

BLDC commutation is always checked electronically and the stator windings must be somewhat energized to rotate the BLDC motor. A knowledge of the rotor position is necessary to ascertain the winding to be energized. Hall effect sensors incorporated in the non-driving end of the motor stator helps in sensing the rotor position Figure 2.3; should the poles of the rotor magnetic move towards the sensors (Hall sensors), signals (high or low) which suggests the N or S pole passing near the sensors will be generated. The commutation order is determined from a combination of the 3 Hall sensor signals [18].

REFERENCES

1. Zhang, J., Wang, N., & Wang, S. (2004, June). A developed method of tuning PID controllers with fuzzy rules for integrating processes. In *American Control Conference, 2004. Proceedings of the 2004* (Vol. 2, pp. 1109-1114).
2. El-Sharkawi, M. A. (1991). Development and implementation of high performance variable structure tracking control for brushless motors. *IEEE Transactions on Energy Conversion*, *6*(1), 114-119.
3. Pearson, W. R., & Sen, P. C. (1984). Brushless DC motor propulsion using synchronous motors for transit systems. *IEEE transactions on Industrial Electronics*, (4), 346-351.
4. Shamseldin, M. A., & EL-Samahy, A. A. (2014, September). Speed control of BLDC motor by using PID control and self-tuning fuzzy PID controller. In *Research and Education in Mechatronics (REM), 2014 15th International Workshop on*(pp. 1-9). IEEE..
5. Neethu, U., & Jisha, V. R. (2012, December). Speed control of brushless dc motor: A comparative study. In *Power Electronics, Drives and Energy Systems (PEDES), 2012 IEEE International Conference on* (pp. 1-5).
6. Devi, K. S., Dhanasekaran, R., & Muthulakshmi, S. (2016, May). Improvement of speed control performance in BLDC motor using fuzzy PID controller. In *Advanced Communication Control and Computing Technologies (ICACCCT), 2016 International Conference on* (pp. 380-384). IEEE.
7. Eti, S. L., & Kumar, N. P. (2014). Closed Loop Speed Control of a BLDC Motor Drive Using Adaptive Fuzzy Tuned PI Controller. *International Journal of Engineering Research and Applications*, *4*(11), 93-104..
8. Karthikeyan, J., & Dhanasekaran, R. (2012). Resonant DC Link Inverter for Brushless DC Motor Drive System. *International Journal of Emerging Electric Power Systems*, *13*(2).

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

9. Yusof, A. M. (2013). *Comparative study of conventional PID and fuzzy-PID for DC motor speed control* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

10. Singh, M., & Garg, A. (2012, December). Performance evaluation of BLDC motor with conventional PI and fuzzy speed controller. In *Power Electronics (IICPE), 2012 IEEE 5th India International Conference on* (pp. 1-6). IEEE.

11. Krishnan, P. H., & Arjun, M. (2014, March). Control of BLDC motor based on adaptive fuzzy logic PID controller. In *Green Computing Communication and Electrical Engineering (ICGCCEE), 2014 International Conference on* (pp. 1-5). IEEE.

12. Xuanfeng, S., & Xingyan, L. (2010, October). BLDC motor speed servo system based on novel P-fuzzy self-adaptive PID control. In *Information Networking and Automation (ICINA), 2010 International Conference on* (Vol. 2, pp. V2-186). IEEE.

13. Rahmani, R., Mahmodian, M. S., Mekhilef, S., & Shojaei, A. A. (2012, December). Fuzzy logic controller optimized by particle swarm optimization for DC motor speed control. In *Research and Development (SCOReD), 2012 IEEE Student Conference on* (pp. 109-113). IEEE.

14. Karthikeyan, J., & Sekaran, R. D. (2011). Current control of brushless dc motor based on a common dc signal for space operated vehicles. *International Journal of Electrical Power & Energy Systems*, *33*(10), 1721-1727.

15. Dixon, J. W., & Leal, L. A. (2002). Current control strategy for brushless DC motors based on a common DC signal. *IEEE transactions on power electronics*, *17*(2), 232-240.

16. Ramesh, M. V., Rao, G. S., Amarnath, J., Kamakshaiah, S., & Jawaharlal, B. (2011, December). Speed torque characteristics of brushless DC motor in either direction on load using ARM controller. In *Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES* (pp. 217-222). IEEE.

17. Yedamale, P., 2003. Brushless DC (BLDC) motor fundamentals. *Microchip Technology Inc*, *20*, pp.3-15.

18. Siong, T.C., Ismail, B., Siraj, S.F. and Mohammed, M.F., 2011. Fuzzy logic controller for BLDC permanent magnet motor drives. *International Journal of Electrical & Computer Sciences IJECS-IJENS*, *11*(02), pp.13-18.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

19. Prasad, K. A., & Nair, U. (2017, February). An intelligent fuzzy sliding mode controller for a BLDC motor. In *Innovative Mechanisms for Industry Applications (ICIMIA), 2017 International Conference on* (pp. 274-278). IEEE.

20. Akin, B., & Bhardwaj, M. (2010). Trapezoidal control of BLDC motors using hall effect sensors. *July, 2013Application Report*.

21. Kota, V., Pasumarthi, V., & Tangirala, Y. Implementation of Different Speed Control Strategies of BLDC Motor.

22. Abd Karim, N. (2014). *Simulation of speed control brushless dc motor using gaussian fuzzy logic controller* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

23. Gambhir, R., & Jha, A. K. (2013). Brushless DC Motor: Construction and Applications. *Int. J. Eng. Sci*, *2*(5), 72-77.

24. Yusof, A. M. (2013). *Comparative study of conventional PID and fuzzy-PID for DC motor speed control* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

25. Pandey, M., Singh, Y. G., & Singh, H. G. (2010). *Analysis of self-tuning fuzzy PID internal model control* (Doctoral dissertation, Universiti Thapar in Patiala, India).

26. Qiu, K., Zheng, Z., & Chen, T. Y. (2017, October). Testing Proportional-Integral-Derivative (PID) Controller with Metamorphic Testing. In *2017 IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW)* (pp. 88-89). IEEE.

27. Kant, M., & Kaur, G. G. (2014). *Comparative analysis of dc motor speed control using various controller tuning methods* (Doctoral dissertation, Universiti Thapar in Patiala, India).

28. Faruq, M. F. B. M. (2008). *PID Controller Design for Controlling DC Motor Speed Using MATLAB Application*. Universiti Malaysia Pahang, Electrical & Electronics Engineering.

29. Li, Y., Ang, K. H., & Chong, G. C. (2006). PID control system analysis and design. *IEEE Control Systems*, *26*(1), 32-41.

30. Youney, J. (2007). *A comparison and evaluation of common PID tuning methods*. Universiti of Central Florida.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

31. Ghani, A., & Akli, M. K. (2014). *Development of PID current control for DC motor using ARDUINO* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

32. Fattah, A. (2015). *Design and Analysis of Speed Control Using Hybrid PID-Fuzzy Controller for Induction Motors*, (degree of Master Universiti Western Michigan).

33. Chin, H. H. (2006). *All Digital design and Implementaion of Proportional-Integral-Derivative (PID) Controller*. University Kentucky (UK).

34. Simoes, M.G., 2010. *Introduction to fuzzy control*. Colorado School of Mines, Engineering Division, Golden, Colorado, *8*, pp.18-22.

35. Zhang, P. (2010). *Advanced industrial control technology*. 1st edition, Oxford, William Andrew, pp.290-298.

36. Shaw, I. S. (2013). *Fuzzy control of industrial systems: theory and applications* (Vol. 457). 1st Johannesburg Republic of south Africa, University Rand Africans, pp.5-15.

37. Bai, Y., & Wang, D. (2006). Fundamentals of fuzzy logic control—fuzzy sets, fuzzy rules and defuzzifications. In *Advanced Fuzzy Logic Technologies in Industrial Applications*, pp. 17-36. Springer London.

38. Almatheel, Y. A., & Abdelrahman, A. (2017, January). Speed control of DC motor using Fuzzy Logic Controller. In *Communication, Control, Computing and Electronics Engineering (ICCCCEE), 2017 International Conference on*(pp. 1-8). IEEE.

39. Nakamatsu, K. (2013). *The handbook on reasoning-based intelligent systems*. World Scientific. Edited by: Kazumi Nakamatsu (*University of Hyogo, Japan*), Lakhmi C Jain (*University of South Australia, Australia*), p.p.63-67.

40. Rambabu, S. (2007). *Modeling and control of a brushless DC motor*. (Degree of Master of Technology In Power Control and Drives National Institute of Technology, Rourkela, Deemed University India).

41. Ali, N. A. (2008). *Fuzzy Logic Controller for Controlling DC Motor Speed using MATLAB Applications* (Doctoral dissertation, UMP Onn Malaysia).

42. Shamseldin, E. M. A. (2016). *Speed Control of High Performance Brushless DC Motor* (Doctoral dissertation, Faculty of Engineering at Helwan University).

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

43. Devi, K. S., Dhanasekaran, R., & Muthulakshmi, S. (2016, May). Improvement of speed control performance in BLDC motor using fuzzy PID controller. In *Advanced Communication Control and Computing Technologies (ICACCCT), 2016 International Conference on* (pp. 380-384). IEEE.

44. Shamseldin, M. A., & EL-Samahy, A. A. (2014, September). *Speed control of BLDC motor by using PID control and self-tuning fuzzy PID controller*. In *Research and Education in Mechatronics (REM), 2014 15th International Workshop on*(pp. 1-9). IEEE.

45. H. C. Lovatt, M. L. McClelland, J. M. Stephenson. *Comparative Performance of Singly Salient Reluctance, Switched Reluctance, and Induction Motors [C]*. The 8th *International Conference on Electrical Machines and Drives*, pp. 361-365, 1997.

46. Yong, Z., Man, W., Qi, L., & Chao, Z. (2016, May). The design of BLDCM controller for EMA based on fuzzy PID control. In *Control and Decision Conference (CCDC), 2016 Chinese* (pp. 6428-6432). IEEE.

47. Arulmozhiyal, R., & Kandiban, R. (2012, July). An intelligent speed controller for Brushless DC motor. In *Industrial Electronics and Applications (ICIEA), 2012 7th IEEE Conference on* (pp. 16-21). IEEE.

48. Krishnan, P. H., & Arjun, M. (2014, March). Control of BLDC motor based on adaptive fuzzy logic PID controller. In *Green Computing Communication and Electrical Engineering (ICGCCEE), 2014 International Conference on* (pp. 1-5). IEEE.

49. Krishnan, P. H., & Arjun, M. (2014, March). Control of BLDC motor based on adaptive fuzzy logic PID controller. In *Green Computing Communication and Electrical Engineering (ICGCCEE), 2014 International Conference on* (pp. 1-5). IEEE.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH